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Abstract

Plasma polarization spectroscopy work done by our group since the 3rd US-Japan PPS Workshop is overviewed. Theoretically, the polarization dependence on various electron distribution functions for He-like, Ne-like, and Ni-like x-ray transitions for a wide range of Z has been investigated. In particular, this study was focused on the polarization dependence for monoenergetic and steep electron distribution functions. The diagnostically important spectral lines and features of K-, L-, and M-shell ions were identified which can be used in x-ray spectropolarimetry of plasma. Importance of polarization-sensitive LLNL Electron Beam Ion Trap data is emphasized. The results of the UNR polarization-sensitive Ti and Mo x-pinch experiments are discussed.

I. Introduction: overview of our polarization spectroscopy work done since the 3rd US-Japan PPS Workshop

The results of theoretical and experimental studies of anisotropic plasma sources such as x-pinch plasmas were reported in [1]. They are based on x-ray line spectropolarimetry, a powerful new tool for investigating anisotropy of high-temperature plasmas. This new diagnostic involves spectroscopic monitoring and modeling of polarization-sensitive x-ray line spectra recorded simultaneously by two spectrometers with different sensitivities to polarization. The difference in these polarization-sensitive spectra indicate polarization of lines caused by anisotropic electron beams and can be used to diagnose the parameters of such beams in plasmas.

Theoretically, the polarization dependence on various electron distribution functions for He-like, Ne-like, and Ni-like x-ray transitions for a wide range of Z has been investigated [2]. The degree of polarization by a monoenergetic electron beam was calculated for all lines using the newly developed, relativistic, multiconfigurational atomic package by M.F. Gu [3]. In particular, this study was focused on the polarization dependence for monoenergetic and steep electron distribution functions. A variety of features was discussed and illustrated such as the polarization dependence on Z, maximum positive and negative polarization near the threshold energy, and zero polarization crossings. The effects of polarization influenced by varying the values of electron temperature, fraction of hot electrons and its cutoff energy was studied. The diagnostically important spectral lines and features of K-, L-, and M-shell ions were identified and discussed. This work provided the best candidates for x-ray spectropolarimetry of high-temperature plasmas with multiply charged ions in a very broad range of the nuclear charge Z from 10 (Ne) up to 79 (Au) [2].

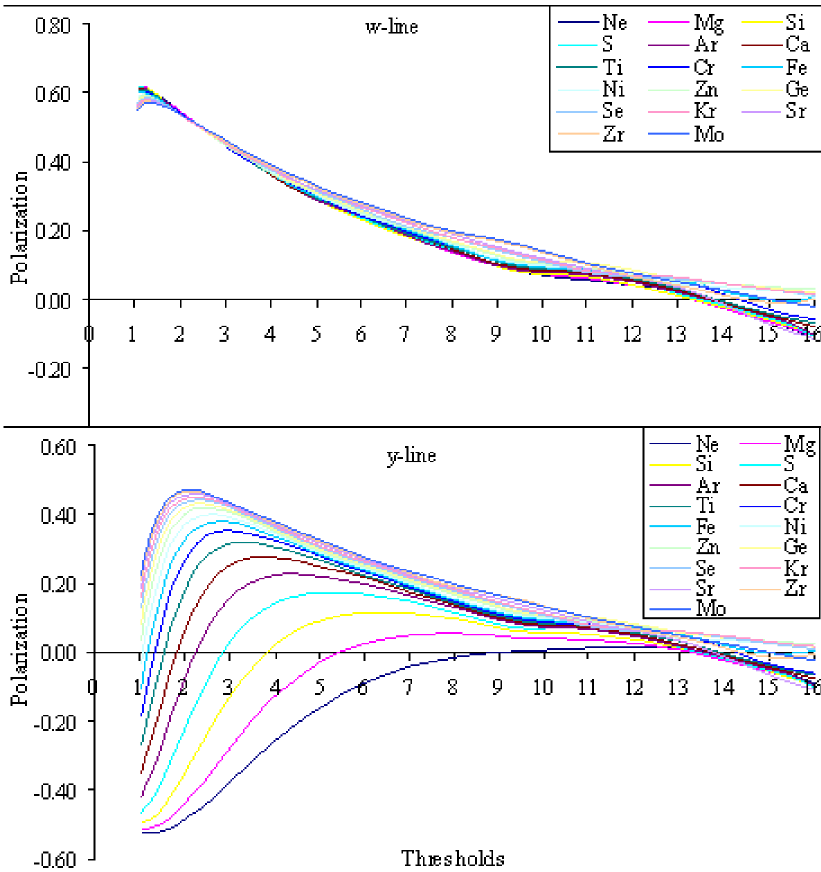
Generation of electron beams in x-pinch plasmas was studied in detail and polarization of soft x-ray radiation was considered along with anisotropy of hard x-rays [4]. The results of Ti and Mo x-pinch polarization-sensitive experiments at UNR were overviewed [1]. In particular, the spectroscopic results from seven Ti and four Mo x-pinch shots were analyzed. Polarization-sensitive spectra from Ti x-pinches were also compared with the similar spectra generated by a quasi-Maxwellian electron beam at the LLNL EBIT-II electron beam ion trap [5]. The analysis of polarization-sensitive x-pinch experiments indicated x-ray line polarization in two Ti and three Mo x-pinch shots.

In general, x-ray line polarization is sensitive not only to the electron distribution function but also to the magnetic field. The magnetic fields in x-pinches were recently estimated to be of the order up to few thousands of tesla but were not measured yet. The possibility of using x-ray spectropolarimetry for measurements of magnetic field in dense hot x-pinch plasma was explored. The design of the new x-ray spectropolarimetry experiments involving the measurements of the magnetic fields was discussed. The standard two spectrometer technique was overviewed and in addition the new three spectrometer measurements were proposed [6-8].

II. Theoretical Study of the Influence of Electron Distribution Functions on X-ray Line Polarization in Plasmas

In laboratory and astrophysical plasmas, the electron distribution function (EDF) may differ from the isotropic Maxwellian distribution, due to the presence, for example, of electron beams. This will lead to the addition of a hot electron component that may be described by Gaussian (almost monoenergetic) or steep electron distribution functions. Although most of the electrons in the plasma may follow the Maxwellian distribution, the contribution of the hot electrons is essential and can affect the emission spectra and many other characteristics of the plasma. For example, beams of hot electrons can lead to polarization of x-ray lines in plasmas. In this work, we theoretically studied the polarization dependence on various electron distribution functions for He-like, Ne-like, and Ni-like x-ray transitions for a wide range of Z. This study will focus on the polarization dependence for monoenergetic and steep electron distribution functions. This work identifies and studies some of the candidates for x-ray spectropolarimetry of high-temperature plasmas with multiply charged ions in a very broad range of nuclear charge Z from 10 (Ne) up to 79 (Au).

In Fig. 1, polarization of the resonance w and intercombination y lines was calculated with a monoenergetic EDF for a broad range of mid-Z elements from Ne (Z=10) up to Mo (Z=42). The electron beam energies are given in threshold units which are listed in Fig. 1 for all considered ions. Polarization of the resonance line w has a maximum at the threshold, then monotonically decreases to zero and only slightly depends on the ion. On the contrary, polarization of the intercombination line y strongly depends on the type of the ion and electron beam energy in particular for lower-Z elements (from Ne to Ni). Specifically, polarization of y line has the minimum values at the threshold (for example, less than –50% for Ne ion), which increases with Z. The maximum value of polarization of y line also increases with Z (it is the largest for the element with the highest Z, for Mo ion) and moves closer to the threshold as Z increases. For higher-Z elements and high electron beam energies polarization of y line approaches polarization of w line.



Threshold energy in eV

	Z	w	y
Ne	10	9.20E+02	9.13E+02
Mg	12	1.35E+03	1.34E+03
Si	14	1.86E+03	1.85E+03
S	16	2.46E+03	2.45E+03
Ar	18	3.14E+03	3.12E+03
Ca	20	3.90E+03	3.88E+03
Ti	22	4.75E+03	4.73E+03
Cr	24	5.68E+03	5.65E+03
Fe	26	6.70E+03	6.67E+03
Ni	28	7.80E+03	7.76E+03
Zn	30	9.00E+03	8.95E+03
Ge	32	1.03E+04	1.02E+04
Se	34	1.16E+04	1.16E+04
Kr	36	1.31E+04	1.30E+04
Sr	38	1.47E+04	1.46E+04
Zr	40	1.63E+04	1.62E+04
Mo	42	1.81E+04	1.79E+04

Fig. 1. Polarization of the resonance line w and intercombination line y of mid-Z ions (Z=10-42) calculated with a monoenergetic EDF for different electron beam energies (in threshold units). Threshold energies are given in Table on the right.

Figs. 2 and 3 illustrate the depolarization effect by a non-monoenergetic EDF, for example, a steep EDF with a cutoff energy Ec and a power γ. Specifically, polarization of line w substantially decreases with the increase of Ec, whereas it only slightly changes (increases) with increase of γ. This effect is almost independent from the type of the ion. On the contrary, with the increase of Ec polarization of line y increases from negative values for lower-Z elements to positive values, whereas polarization of higher-Z elements decreases. As a result, polarization of y line becomes less dependent on the type of the ion as Ec increases from 1 to 3 (in threshold units). Polarization of y line is almost independent from a power γ.

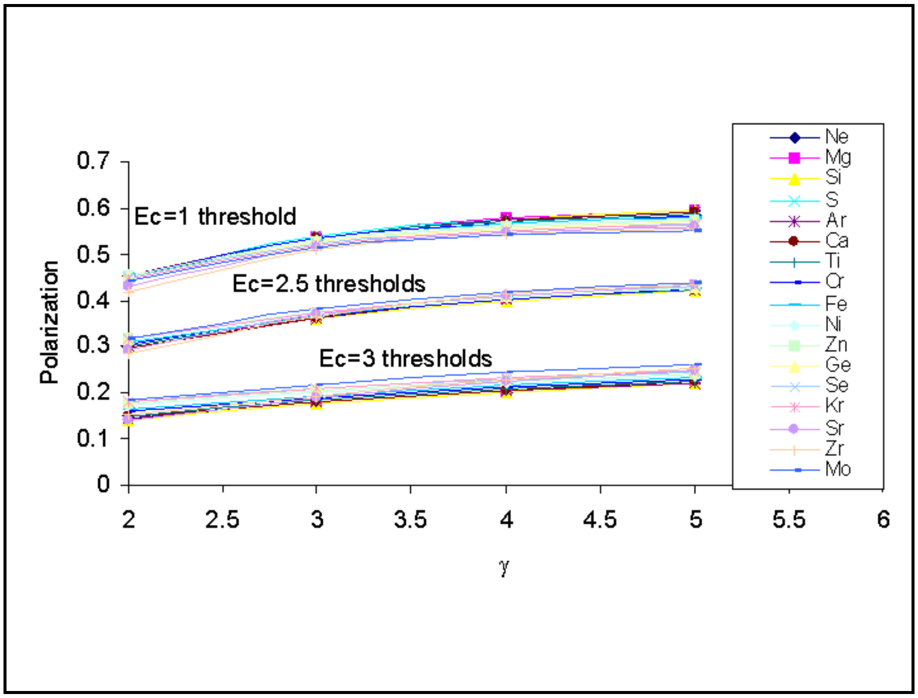


Fig. 2. Polarization of the resonance line w calculated with a steep EDF for different values of a cutoff energy Ec=1, 2.5, and 3 (in threshold units) and a power γ=2-5.

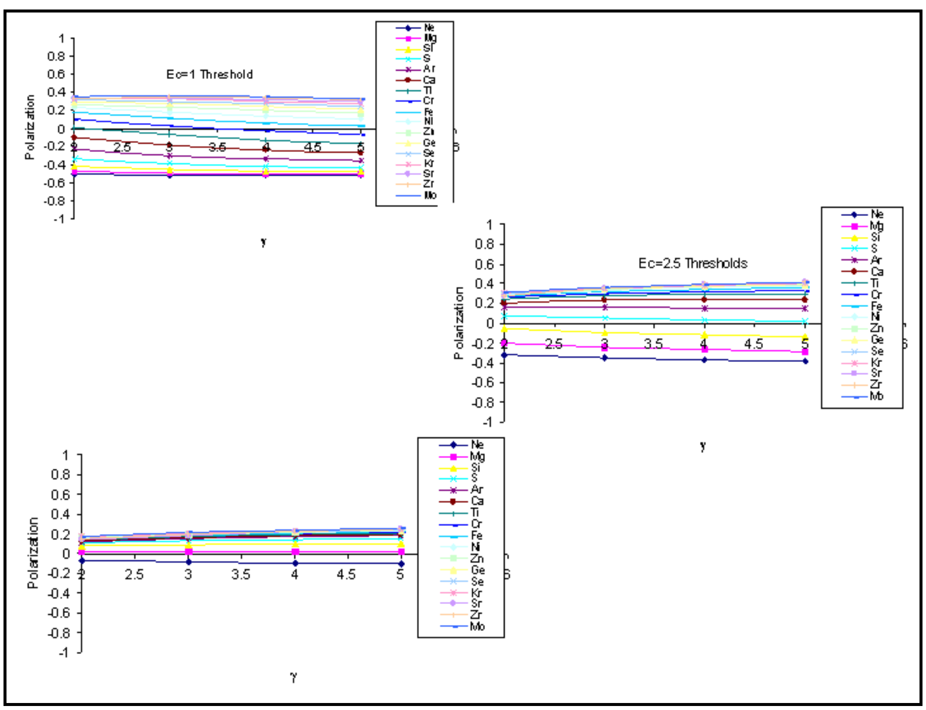


Fig. 3. Polarization of the intercombination line y calculated with a steep EDF for different values of a cutoff energy Ec=1, 2.5, and 3 (in threshold units) and a power γ=2-5.

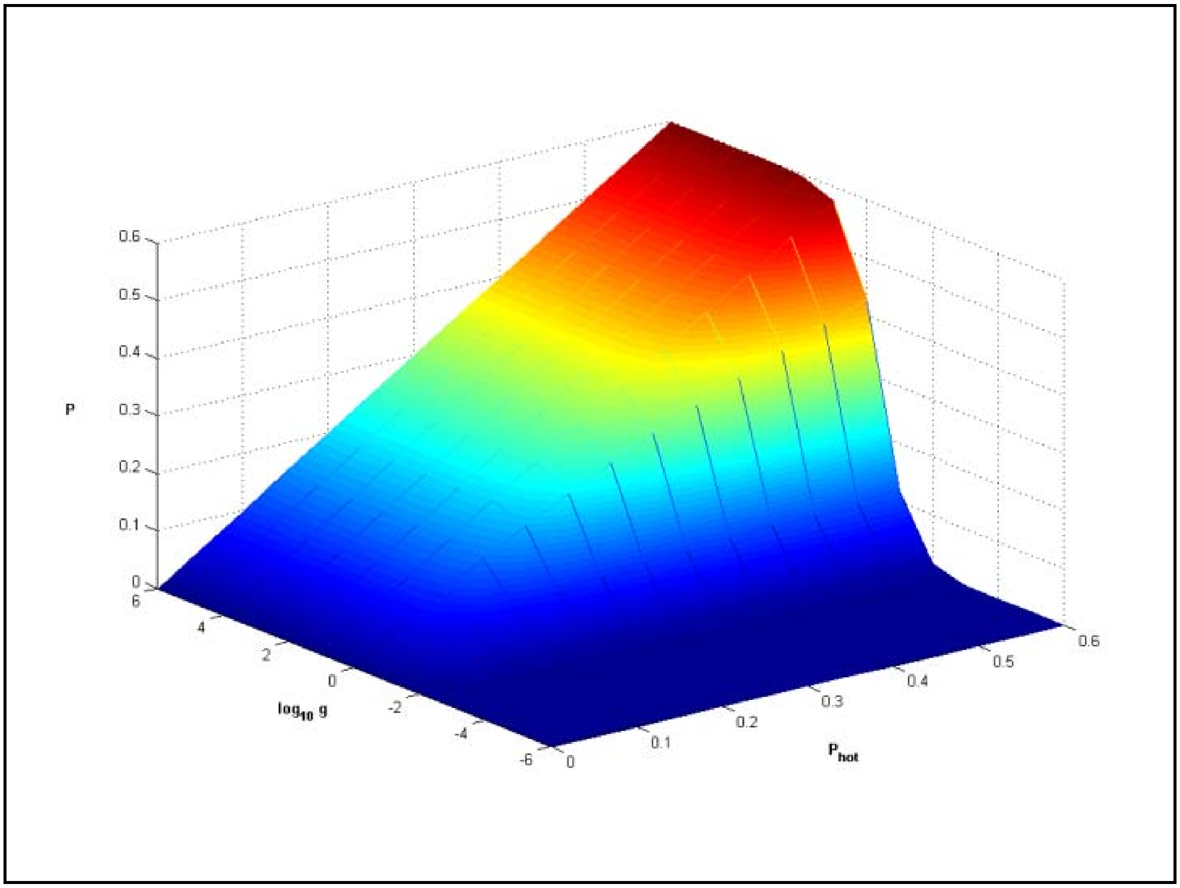
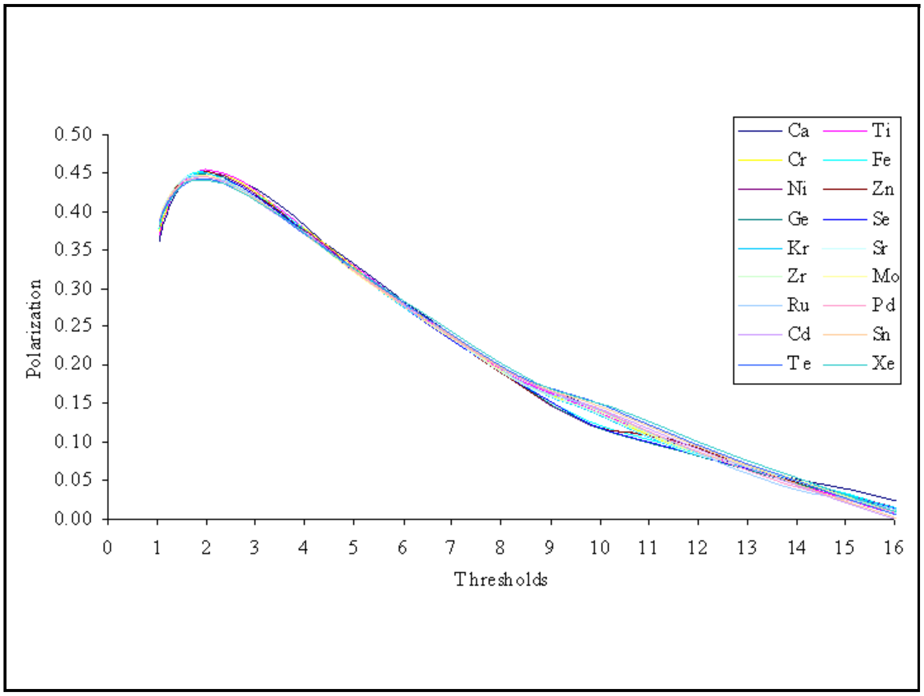


Fig. 4. Illustration of depolarization of the resonance line w by Maxwellian electrons in plasmas. P is polarization in plasma with Maxwellian and non-Maxwellian, hot electrons; Phot is polarization in plasma with only non-Maxwellian, hot electrons; and g is the ratio of the excitation rates of non-Maxwellian and Maxwellian electrons.

Fig. 4 illustrates depolarization caused by Maxwellian electrons in plasmas. Line polarization in plasmas strongly depends on the fraction of non-Maxwellian, hot electrons (with respect to the total electron density). In general, the fraction of 3-5% is sufficient to observe line polarization of 5-10% (assuming the maximum polarization more than 50%).

Figs. 5 and 6 show the results of calculations of polarization of Ne-like lines. In particular, polarization of one of the most intense Ne-like lines, 3C line calculated in threshold units for ions from Ne-like Ca (Z=20) up to Xe (Z=54) together with threshold energies for these ions are presented in Fig. 5. Polarization of diagnostically important 3A-3F lines calculated for Mo ions is given in Fig. 6. These results agree well with calculations by Zhang et al [9], which are listed up to six thresholds and with the polarization of Ne-like Fe lines produced at the LLNL EBIT [10]. The degree of polarization of 3C and 3D lines are close and smaller than for 3A, 3B, 3F, and 3G lines. The 3C and 3D lines are mostly collisionally excited and in the first approximation we can use present theoretical predictions whereas polarization of the other lines is affected by radiative cascades and requires full kinetic modeling.



Threshold Energy [eV]		
	Z	3C
Ca	20	401.90
Ti	22	525.91
Cr	24	665.57
Fe	26	821.11
Ni	28	992.80
Zn	30	1180.90
Ge	32	1385.80
Se	34	1607.70
Kr	36	1847.00
Sr	38	2104.10
Zr	40	2379.30
Mo	42	2675.70
Ru	44	2985.80
Pd	46	3318.10
Cd	48	3670.40
Sn	50	4043.30
Te	52	4437.30
Xe	54	4853.20

Fig. 5. Polarization of Ne-like line 3C calculated with a monoenergetic EDF for different electron beam energies (in threshold units). Threshold energies are given in Table on the right.

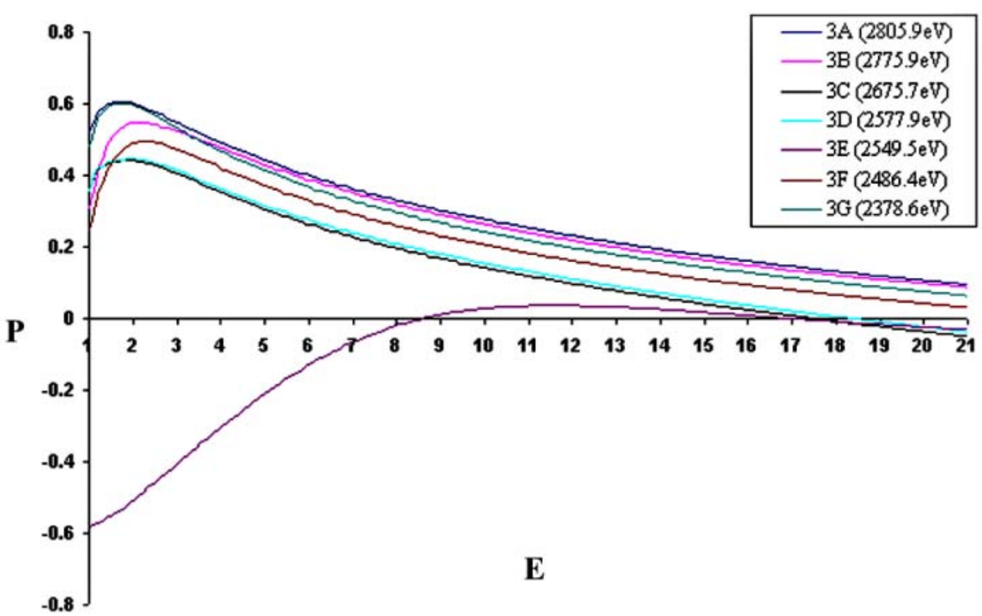
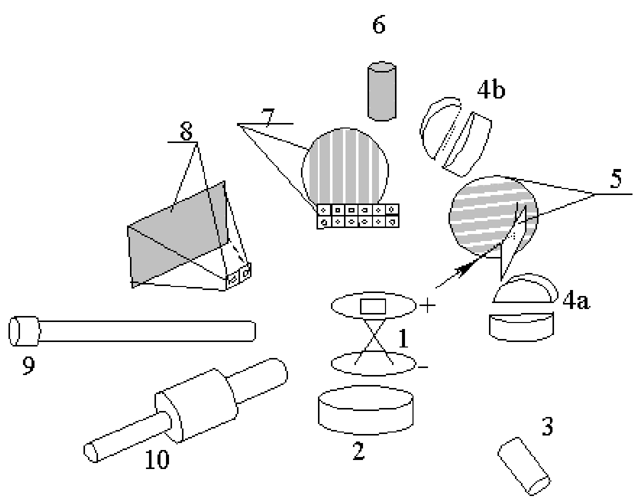


Fig. 6. Polarization of Ne-like lines 3A-3F calculated with a monoenergetic EDF for different electron beam energies (in threshold units). Threshold energies are given in a box on the right.

III. X-ray spectropolarimetry in Ti and Mo x-pinch experiments

X-pinches produce a bright, small x-ray source with a well-defined location. They can yield x-ray spectra from numerous ions with very high resolution. Currently, x-ray spectra of x-pinches are collected and studied at different types of pulsed power machines, for example, at the 1 MA pulsed power device at University of Nevada, Reno (UNR) [11]. A distinct feature of x-pinches is the existence of plasma anisotropy in the form of strong electron beams, which makes them attractive objects for spectropolarimetry. X-ray spectropolarimetry is a new diagnostic that can provide detailed information about the electron distribution function in plasmas. This diagnostic is based on spectroscopic monitoring of the plasma and modeling of the polarization-sensitive spectra. Such spectra are simultaneously recorded by two crystals with different sensitivity to polarization. The difference in line ratios from two simultaneously recorded spectra yields information on the parameters of electron beams such as a fraction of hot electrons and an energy cutoff. Polarization-sensitive experiments were performed on the 1 MA pulsed power Z-pinch device at the UNR Nevada Terawatt Facility for Ti and Mo x-pinches (see for details [1]). The scheme of the x-pinch experiments involving polarization-sensitive measurements is given below.



1. X-pinch load; 2. Horizontal space-resolved convex crystal spectrometer with a low resolution time-integrated pinhole camera; 3. Collimated hard x-ray *Si*- diode; 4. (a) Side-on convex crystal polarimeter; (b) End-on convex crystal polarimeter; 5. Flat crystal time-gated spectrometer; 6. Hard x-ray detector (outside vacuum chamber); 7. Time-gated pinhole camera; 8. High resolution pinhole camera; 9. PCD, XRD and Ni bolometer assembly; 10. Polychromator and transmission grating spectrometer assembly.

Fig. 7. The scheme of x-pinch experiments involving polarization-sensitive measurements.

A planar-loop configuration was used for x-pinch loads (labeled 1 in Figure 7) in which the top and the bottom wire loops were touching each other only at one central point. The polarization-dependent spectra of K-shell line radiation from Ti x-pinches and L-shell line radiation from Mo x-pinches were recorded by a polarimeter which includes so-called horizontal (H) and vertical (V) spectrometers (labeled 4a in Figure 7). The "H" spectrometer has a dispersion plane perpendicular to the discharge axis and records mostly the parallel polarization state. The "V" spectrometer has a dispersion plane parallel to the discharge axis and records mostly the perpendicular polarization state. The crystals for Ti and Mo x-pinch measurements were selected to provide the value of a nominal Bragg angle close to 45°. For Ti x-pinches, LiF (2d=4.027Å) crystals were used with a spacing corresponding to the nominal Bragg angle of 40° at the wavelength of 2.62 Å (w line). For Mo x-pinches, α-quartz (2d=6.687Å) crystals with a spacing corresponding to the nominal Bragg angle of 46° at the wavelength of 4.8 Å (3D line) were employed.

Ti results: Earlier, preliminary results of x-ray spectropolarimetry studies of Ti x-pinches at UNR were presented in [12-13]. Recently, spectroscopic results from seven Ti x-pinch shots have been analyzed [5]. Similar K-shell Ti polarization-dependent spectra generated by a quasi-Maxwellian electron beam at the LLNL EBIT-II electron beam ion trap have been studied [5] and compared with previous LLNL EBIT studies with a monoenergetic electron beam [14]. In [14], the x-ray spectrum of He-like Ti was measured at the energy just above the electron-impact excitation threshold (4800 eV). The measured intensities were collected by the spectrometers with a crystal recording almost a pure parallel polarization state (I_1) and a crystal recording a mixture of both polarization states (I_2) [14]. In [5] we use the same technique to measure polarization-sensitive Ti spectra generated by a quasi-Maxwellian electron beam which was set to model a quasi-Maxwellian distribution function with T_M=2.3 keV in the energy range up to 11.85 keV (2.5 excitation threshold). The measured intensities simultaneously recorded by the spectrometers with a Si (220) crystal (almost a pure parallel polarization state, I_3) and a Ge (111) crystal (mixture of both polarization states, I_4) were I_3=0.212, I_4=0.335 for z/w; I_3=0.068, I_4=0.145 for x/w; and I_3=0.113, I_4=0.153 for y/w. Theoretical modeling of He-like Ti lines with Gaussian and quasi-Maxwellian electron distribution functions was performed to match less-sensitive to polarization data I_2 and I_4. The theory describes well the ratios and differences in spectra between monoenergetic and quasi-Maxwellian beams, specifically the fact that the ratio z/w does not change, but the x/w ratio decreases from 0.191 to 0.145 and the y/w ratio also decreases from 0.235 to 0.153. The comparison of polarization-sensitive ratios I_1/I_2 and I_3/I_4 for the z, x, and y lines prove that: the ratio decreases for the lines z and x and they become more negatively polarized and the ratio increases for the line y, which become more positively polarized. This agrees well with theoretical predictions.

Mo results: Modeling of experimental Mo x-pinch spectra together with the most intense and diagnostically-important L-shell spectral features including the Ne-like lines (3A-3G) are shown in Fig. 8. The results of this modeling was discussed in detail in [11]. Ne-like lines are the best candidates for L-shell spectropolarimetry because only Ne-like lines are single lines and also theoretical calculations predict strong polarization of lines 3C and 3D near the threshold. Results of modeling presented in Fig. 8 indicate the presence of hot electrons with a fraction from 3 up to 7 % which provides justification of using such Mo x-pinches for x-ray spectropolarimetry. The typical polarization-sensitive spectra from Mo X-pinches are presented in Fig. 9. Analysis of four Mo X-pinch shots shows that the H and V traces are different for shots 91, 92, and 93 and are almost identical for the shot 97. The intensities associated with different polarization states $I_{II}/I_{\perp}$ for each of the spectral lines (3A, 3B, F1, 3C, and 3D) and the line ratios of the satellite lines to their resonance lines (Na2/3C) from the horizontal and vertical spectra have been analyzed. In this analysis, we used theoretical predictions discussed in a previous section. Experimental values of $I_{II}/I_{\perp}$ for the line ratio 3D/ 3C was found to be close to 1 for all shots, which indicates the same polarization for the 3C and 3D lines and agrees well with theory. Experimental values of $I_{II}/I_{\perp}$ for other lines are greater than 1, which gives a positive polarization compared to resonance lines using the two spectrometer technique. Analysis of four Mo x-pinch shots indicates polarization of x-ray L-shell lines was significant in three shots (91, 92, and 93) and was not significant in the shot 97.

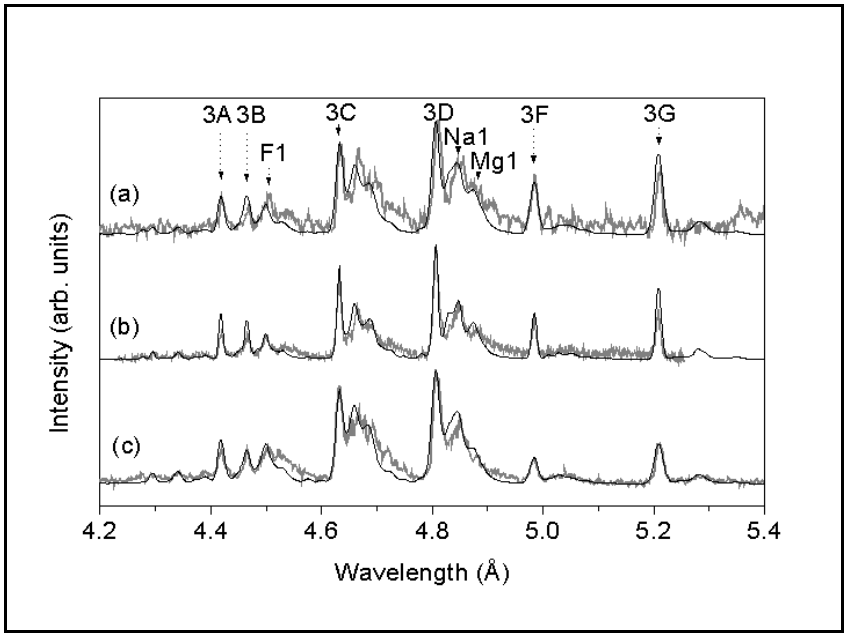


Fig. 8. Experimental spectra (gray lines) from Mo x-pinches of various wire diameters fit with modeled spectra (black lines). (a) 62 μm wire pinch and the modeled spectrum has 7% hot electrons, T_e = 850eV, and $n_e = 2.1x10^{21} cm^{-3}$. (b) 50 mm wire pinch and the modeled spectrum has 4.5% hot electrons, T_e = 850eV, and $n_e = 5x10^{21} cm^{-3}$. (c) 24 mm wire pinch and the modeled spectrum has 3% hot electrons, T_e = 825eV, and $n_e = 2x10^{22} cm^{-3}$.

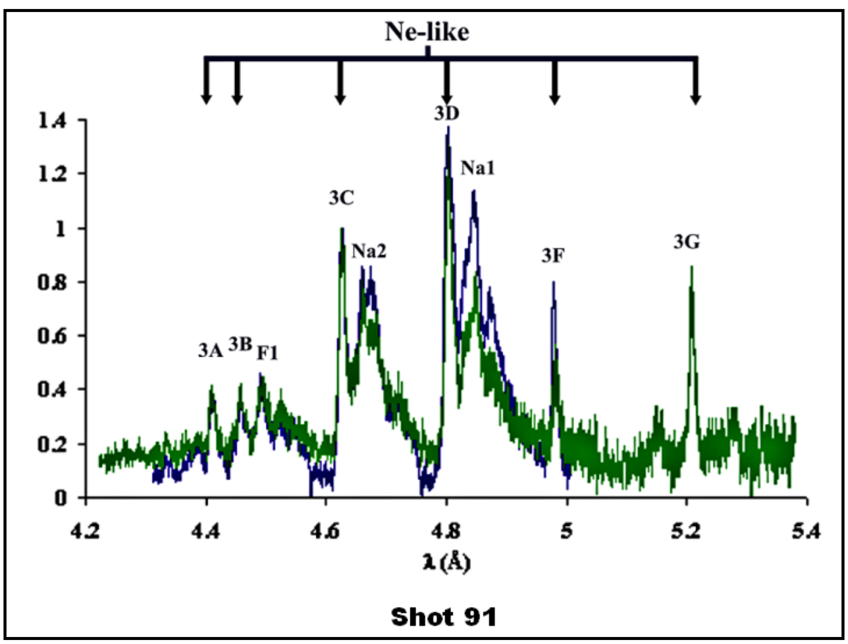


Fig. 9. X-ray polarization-sensitive spectra from a Mo X-pinch recorded by H (blue lines) and V (green lines) spectrometers.

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